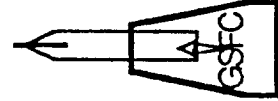


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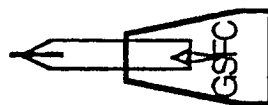
COLLISION AVOIDANCE SENSOR SKIN

SSF Evolution Conference

Houston, TX

August 6,7,8 1991

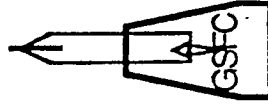
Collision avoidance is a prime safety concern for space operations as cited several times in the Fischer-Price report. Computer modelling, augmented by cameras, is currently the preferred robot collision avoidance technique. Because of the several obvious problems inherent with computer modelling listed on the slide, there are many who would prefer a sensor-based system. But what sensor system? Vision systems have problems associated with lighting, blind spots and lack of precision in determining precisely where an object is. Also, they require a lot of computer power, especially when machine vision is involved. Lasers are outstanding for determining range and edges and they are not bothered by lighting conditions or the sun but, they have serious blind spots and, when scanning is used (as frequently it must be), they become complex and computationally intensive. An array is perhaps the best solution in terms of totally eliminating blind spots. But, these are inherently range limited (particularly capacitive and inductive), are computationally intensive, have too many I/O lines (if the pixel sizes are small) and, since they cover the entire surface of the robot arm, disturb the form factor of the system. They tend to upset the thermal system, bulk up the arm and emit omni-directional EMI. Electro-optical arrays tend to be blinded by the sun and inductive arrays are sensitive to the conductivity and/or magnetic properties of the materials they are encountering. The ideal solution would be an array, to eliminate blind spots, range on the order of one (1) foot, minimal pixel numbers (no imaging), ability to locate an object (precision sufficient for collision avoidance), and no disturbance to the robot form factor. For most of these requirements save range and edge determination, a capacitive system coupled with a vision camera is best. Is it possible to develop a capacitive array with relatively long range (on the order of one (1) foot) which can determine edges (sufficient for collision avoidance) and which does not require imaging and a large number of pixels?



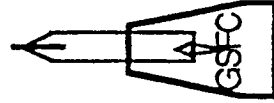
BACKGROUND AND HISTORY

- Collision Avoidance A Prime Safety Concern in Space
(Cited Several Times in Fischer-Price)
- Sensory - Driven And Computer Modelling
Two Main Approaches
- Computer Modelling Disadvantages
 - Omissions
 - Location Uncertainties
 - Data Intensive And Inefficient
 - Unexpected Event Difficulties
- Vision/Laser Disadvantages
 - Field of View Blind Spots
 - Lighting Conditions (Visions)
 - Scanning Requirements (Laser)
 - Computer Requirements (Imaging Only)
- Array Disadvantages
 - Range Limitations (Capacitive, Inductive)
 - Form Factor Problems (EO)
 - Computer Requirements (Imaging Only)
 - I/O's (Imaging Only)
 - Material-Sensing (Inductive)
 - Sensing To Sun (EO)

What If A Capacitive Array Could be Found With Sufficient
Range and Did Not Require Imaging?

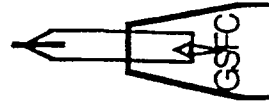


The objective of this project started out to be an ambitious one. It soon got even more ambitious. We wanted to totally eliminate the possibility of a robot (or any mechanism for that matter) inducing a collision in space operations. We were particularly concerned that human beings were safe under all circumstances. It appears this has been accomplished. As will be shown during this presentation, GSFC has a system that is ready for space qualification and flight. But, it soon became apparent that much more could be accomplished with this technology. Payloads could be made invulnerable to collision avoidance and the blind spots behind them eliminated. This could be accomplished by a simple, non-imaging set of "Capaciflector" sensors on each payload. It also is evident that this system could be used to align and dock the system with a wide margin of safety. Throughout, lighting problems could be ignored, and unexpected events and modelling errors taken in stride. At the same time, computational requirements would be reduced. And, this can be done in a simple, rugged, reliable manner that will not disturb the form factor of space systems. It will be practical for space applications. The lab experiments indicate we are well on the way to accomplishing this. Still, the research trail goes deeper. It now appears that the sensors can be extended to End Effectors to provide precontact information and make robot docking (or any docking connection) very smooth, with minimal loads impacted back into the mating structures. This type of ability would be a major step forward in basic controls techniques inspace. There are, however, baseline and restructuring issues to be tackled. The payloads must get power and signals to them from the robot or from the Astronaut servicing tool. This requires a standard electromechanical interface. Any of several could be used. The GSFC prototype shown in this presentation is a good one. And, sensors with their attendant electronics must be added to the payloads, End Effectors and robot arms and integrated into the system.

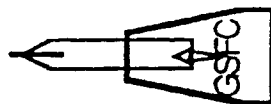


OBJECTIVES

- Why Are We Doing This Project?
 - Eliminate The Danger of Robot (Mechanism)
 - Induced Collisions
- What Benefits Can Be Expected From This Applications?
 - Collision Avoidance Risk Near Zero
 - Less Force Impact While Docking, Controls Much Smoother
 - Unexpected Events, Model Errors Less Dangerous
 - Lighting Problems Significantly Reduced
 - Computational Requirements Reduced
- What Baseline And Restructuring Issues Are Tackled?
 - Sensors Electronics, Standard Interfaces Added To Payload And Robot

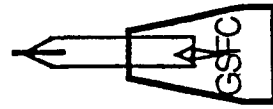


The approach used in the GSFC collision avoidance project is described to include several demonstrations and experimental highlights which are illustrated on video. The "Capaciflector" sensor is central to the collision avoidance system and its suitability for use in space is described in detail. It will be shown that this sensing system is outstanding for space use and ,indeed, has already gone through most of the space qualification criterion. It will also be shown that sensory-based controls employing the "Capaciflector" sensor has potential that is significant and far reaching for robotics in general; much more so than has generally been recognized.

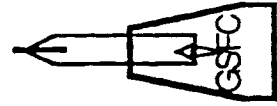


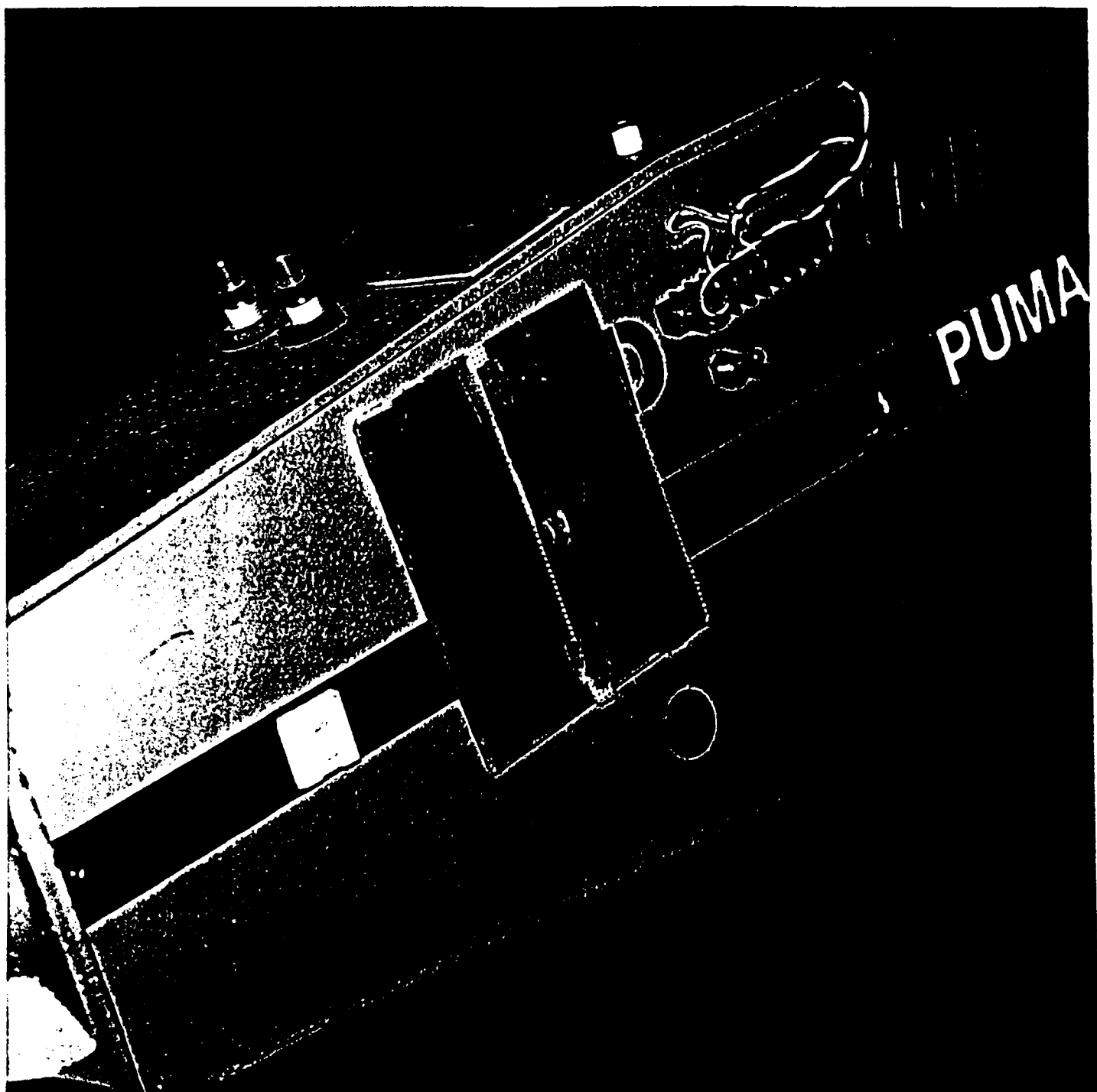
APPROACH

- Project Approach/Results to Date
(Work done in-house at GSFC)
- Efforts Towards Ensuring
Space Suitability
- Potential Of Technology



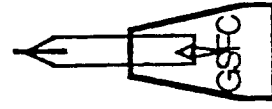
This photo shows a single element "Capaciflector" sensor mounted on a Puma robot arm. It performed computer-controlled collision avoidance at ranges in excess of one foot. The photo shows the simplicity of the device. The sensor is the thin strip of copper tape (1/4 in. wide) between the two black screws. The "Capaciflector" driven shield is the (4 in. X 4 in.) rectangle of copper tape behind the sensor. The electronics is mounted behind the sensor inside the robot arm. But, the Puma arm is grounded, and it is common knowledge that the range of a capacitive-type sensor is only about one (1) in. when it is near a ground plane. How, then, does the GSFC sensor achieve ranges in excess of one (1) foot?

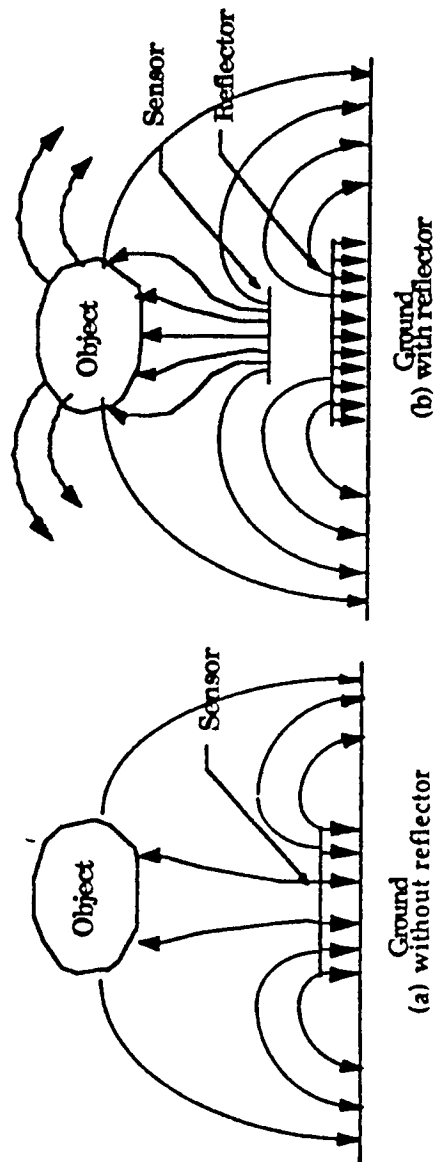




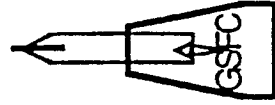
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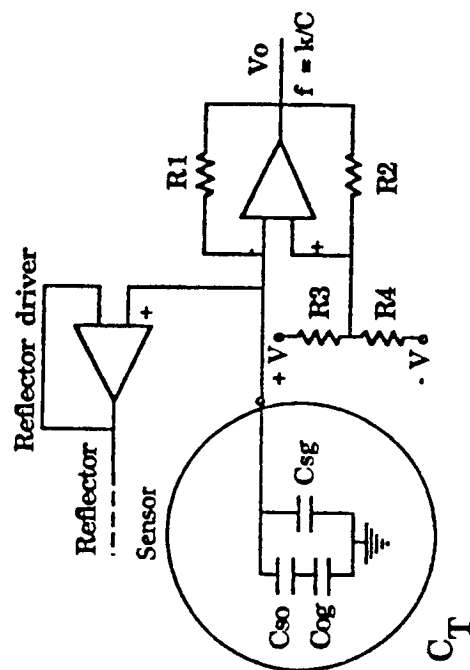
This pair of diagrams explains the "Capaciflector" principle. The diagram on the left shows a normal capacitive sensor in the presence of a ground plane. Most of the electrical field lines couple into the ground plane with only a few projecting outwards to sense the object (and then complete the circuit back to ground). This results in a very poor signal-to-noise ratio and reduced range and sensitivity. This is normally improved by "standing the sensor off" from the ground plane (and adding to robot bulk in the process). The diagram on the right shows the "capaciflector" approach. A reflective shield is inserted between the sensor and the ground plane. This shield is driven at the same frequency and at the same potential as the sensor. Hence the electric field lines from the sensor must travel around the shield in order to reach ground. In the process, more of them are "reflected" towards the object, significantly improving range and sensitivity at no penalty in "stand-off". The shield acts as a capacitive reflector, hence the descriptor "Capaciflector".



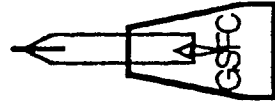


This diagram illustrates the simplicity of the electronics circuitry. It also shows how the driven shield is integrated into the circuit. It should be noted that the shield is electrically isolated from the sensor. It does not "see" an object even though it is at the same potential and frequency as the sensor and even though it follows the sensor as the oscillator changes frequency.



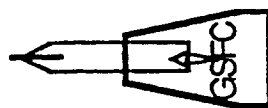


This photo shows a four (4) element array mounted on the Puma robot arm, each of which is identical to the single element example. These sensors are equally spaced across the robot arm. It is almost impossible to see the sensors. They are covered with Kemglaze A276 flight paint and are made of flight-qualified materials throughout. Even the stickers are flight-qualified and the electronics is mil spec. This array has been examined for EMI, thermal conductivity, safety and power consumption. It could be qualified for flight now. The "Capaciflector" performs right through the paint and stickers as if they were not there. Computer-controlled collision avoidance with ranges in excess of one (1) foot is routinely performed with this device.



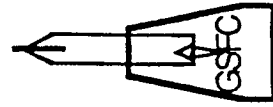
NSA
Godpheard Space Flight Center

Capacitance sensing operates exceptionally well in a vacuum, even better than in air. Also, the lack of humidity changes in space is an advantage. This sensor senses any thing that either conducts electricity or has a significant dielectric constant. And, that turns out in practice to be nearly every thing (paper, wood, styrofoam, plastic). It sees humans, graphite, aluminum (and other metals) extremely well. There is virtually nothing we know of on orbit that it will not see or that is not in the vicinity of something it can sense. It is immune to all but deliberate EMI jamming and a study proves that it will easily meet Shuttle (and Space Station) requirements for EMI emissions-it is low power and low frequency (approx. 30 khz). It is thermally conductive and thermal paints can be applied right over it so from a thermal stand point it isn't present. Also, it doesn't appear to be bothered by temperature changes. New phase-correcting circuitry and a crystal-controlled oscillator will permit it to operate indefinitely with minimal drift. Also, it is indifferent to lighting condition difficulties.



SPACE SUITABILITY

- Outstanding performance in vacuum
- Senses every expected obstacle in orbit
- Outstanding for humans, structural members, thermal blankets
- Independent of lighting conditions
- Outstanding characteristics in EMI, thermal conductivity, temperature tolerance
- Minimal electrical and compute power requirements.
- Minimal wires, leads, I/O's
- Outstanding form factor
- Simple, rugged, reliable, proven technology
- Indefinite operation w/minimal drift

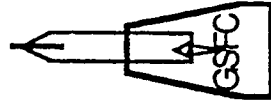


ARM COLLISION AVOIDANCE

ARRAY

IS READY TO QUALIFY AND BE

PUT IN USE NOW



The payload is the most vulnerable region in collision avoidance. It is the object that sticks out the furthest and it is also the region that the camera cannot see behind. It has blind spots. An array of "Capciflectors" can easily be added to each Orbital Replacement Unit (ORU) and eliminate these blind spots. Our calculations and lab experiments indicate that not many sensors would be needed (typically 4 to 8) and power, leads, circuitry and compute power would not be burdensome. With these sensors, one could practically ensure that the ORU would not collide with anything no matter what the circumstances. That is, even if the computer model is in error, an unexpected event occurs, the operator is inattentive, lighting conditions are misleading or blind spots are encountered, the ORU will still not experience a collision. Clearly with the enormous emphasis on safety and the value of the ORU payloads, this sensing protection will be essential. The only question is whether power and signals can be sent between the robot and the payload. As will be shown in the next slide they certainly must and can. It also turns out, that our lab experiments have shown that payload collision avoidance can be extended to include docking; even in a cluttered environment in which several payloads are placed close together. The docking accuracy of the "Capaciflector" to a simple coded passive element in the attachment region is surprisingly good; several times better than what is required for docking. And, it seems apparent that the same techniques in collision avoidance and docking should be extended to the End Effectors themselves. GSFC has also begun this research starting with the robot attachment mechanism (foot). This slide shows a photo of the GSFC robot foot. Conceived, designed and developed in-house at GSFC, this device has been incorporated into the Flight Telerobotic Servicer (FTS) End Item Specification and can attach the (FTS) to the Space Station structure with sufficient repeatability and strength to meet all requirements. Also, it can make all necessary electrical power and electronics and fiber optics signal connections. A miniaturized version of this (approximately the size of a coffee cup) is in fabrication to serve



FURTHER POTENTIAL APPLICATIONS

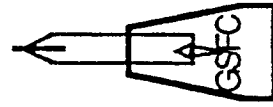
- Payloads(including Orbital Replacement Units)

Collision avoidance

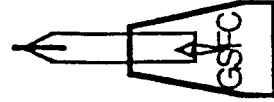
Blind spot elimination

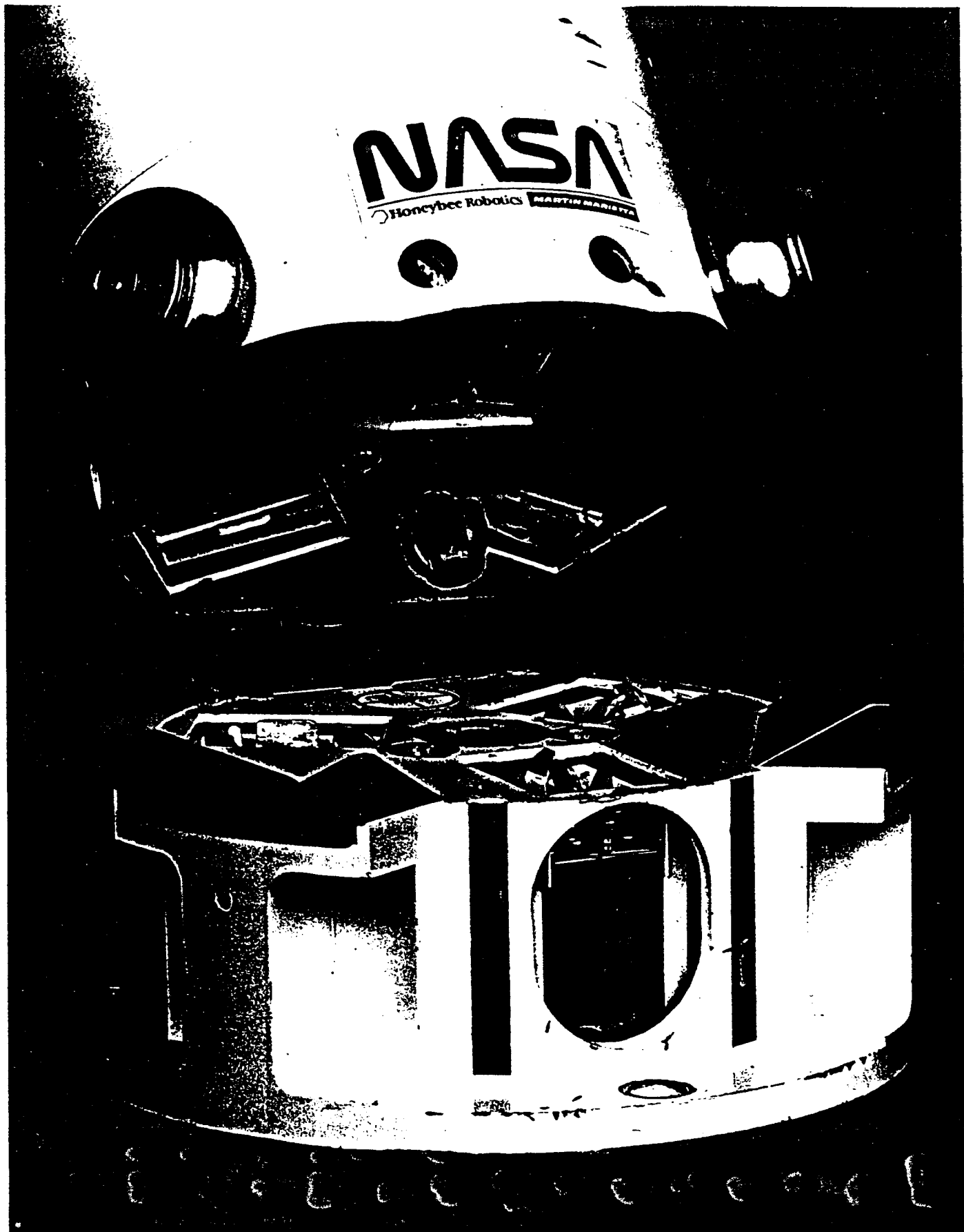
Safe, simple docking

- End Effector collision avoidance and docking



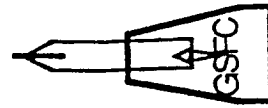
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Capacitance sensing operates exceptionally well in a vacuum, even better than in air. Also, the lack of humidity changes in space is an advantage. This sensor senses any thing that either conducts electricity or has a significant dielectric constant. And, that turns out in practice to be nearly every thing (paper, wood, styrofoam, plastic). It sees humans, graphite, aluminum (and other metals) extremely well. There is virtually nothing we know of on orbit that it will not see or that is not in the vicinity of something it can sense. It is immune to all but deliberate EMI jamming and a study proves that it will easily meet Shuttle (and Space Station) requirements for EMI emissions-it is low power and low frequency (approx. 30 khz). It is thermally conductive and thermal paints can be applied right over it so from a thermal stand point it isn't present. Also, it doesn't appear to be bothered by temperature changes. New phase-correcting circuitry and a crystal-controlled oscillator will permit it to operate indefinitely with minimal drift. Also, it is indifferent to lighting condition difficulties.



DIRECTIONS IN SENSOR DEVELOPMENT

- Flight applications and prototype testing (in cooperation with JSC and Astronauts)

- Phase-correcting circuits

Cross-talk rejection

Improved performance

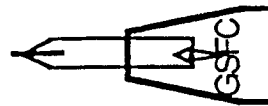
Indefinite operation in space

Simpler, more compact circuits

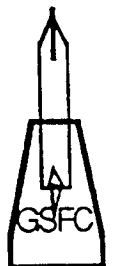
- VLSI electronics/flexible PC sensors and arrays

- Imaging arrays (in cooperation w/ARC)

- Commercial sensors (in cooperation w/Industry)

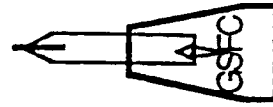


In exploring the sensory-based collision avoidance problem it soon became clear that this technology kept going deeper; first arm collision avoidance, then payload collision avoidance, then payload docking, then End Effector collision avoidance and docking. Apparently a missing key in the hierarchy of sensors has been found. We now have vision, collision avoidance, precontact forces and contact (tactile) forces. In the past, collision avoidance and precontact forces have been missing. In the animal world we see an example of this in the whiskers on a cat which enables it to go through small holes in the dark. The "Capaciflector" system provides electric field whiskers for robots and payloads. This has very significant and fundamental implications for robot control strategies. Adaptive control techniques are much improved resulting in smoother, safer, more precise and efficient performance. We have much more information where and when we need it so computer modelling will yield somewhat to local sensory-based information. At the same time, computer modelling information will be combined with local path planning strategies and enable the robot to perform limited search routines to verify the environment before it begins docking. The operator can be involved as needed. For example, if the model and the sensor disagree, the robot can back up and signal the operator to take a look and resolve the disagreement. And, the operator will now be able to "feel" precontact/proximity forces. But, even though we will have more information at the local site where we need it, the total required information can be reduced.



POTENTIAL FOR FUNDAMENTAL ADVANCES

- Hierarchical sensory-based strategy
- Smoother, safer, more precise performance
- Emphasis toward sensor-based system from computer modelling
- Docking strategies based on computer modelling combined with local path planning reinforced by sensor in formation
- Less computer power required
- Modelling errors and unexpected event dangers reduced
- Teleoperators "feel" precontact forces



SUMMARY

- Collision avoidance skin for robot arms ready for integration into space system (work done in-house at GSFC)
- Work progressing on payload collision avoidance, docking and commercial sensor (work done in-house at GSFC)
- Fundamental advances in robot controls, path planning and operational strategies are now possible (perhaps inevitable)

